Particle Detector Systems for LENR – Low Count Rate Particle Measurements

Bob Ledoux, Program Director

October 21st, 2021

Outline

- Nuclear Products from Fusion Reactions
- Range and Energy Loss
- State of the Art Particle Detectors and Systems
- Experimental Setup and Analysis Discussion

Fusion and Detector Reactions

(1)	$^{2}_{1}D$	+ $^{3}_{1}T$	$\rightarrow$	$^{4}_{2}He$	(3.52 MeV)	+ n^0	(14.06 MeV)			Mono-energetic
(2i)	$^{2}_{1}D$	+ $^{2}_{1}D$	$\rightarrow$	$^{3}_{1}T$	(1.01 MeV)	+ p^+	(3.02 MeV)			50%
(2ii)			$\rightarrow$	$^{3}_{2}He$	(0.82 MeV)	+ n^0	(2.45 MeV)			50%
(3)	$^{2}_{1}D$	+ $^{3}_{2}He$	$\rightarrow$	$^{4}_{2}He$	(3.6 MeV)	+ p^+	(14.7 MeV)			
(4)	$^{3}_{1}T$	+ $^{3}_{1}T$	$\rightarrow$	$^{4}_{2}He$		+ 2 n^0	3-body		+ 11.3 MeV	
(5)	$^{3}_{2}He$	+ $^{3}_{2}He$	$\rightarrow$	$^{4}_{2}He$		+ 2 p^+			+ 12.9 MeV	
(6i)	$^{3}_{2}He$	+ $^{3}_{1}T$	$\rightarrow$	$^{4}_{2}He$		+ p^+	+ n^0		+ 12.1 MeV	57%
(6ii)			$\rightarrow$	$^{4}_{2}He$	(4.8 MeV)	+ $^{2}_{1}D$	(9.5 MeV)			43%
(7i)	$^{2}_{1}D$	+ $^{6}_{3}Li$	$\rightarrow$	2 $^{4}_{2}He$	+ 22.4 MeV			Branching ratio		
(7ii)			$\rightarrow$	$^{3}_{2}He$	+ $^{4}_{2}He$	+ n^0			+ 2.56 MeV	
(7iii)			$\rightarrow$	$^{7}_{3}Li$	+ p^+				+ 5.0 MeV	
(7iv)			$\rightarrow$	$^{7}_{4}Be$	+ n^0				+ 3.4 MeV	
(8)	p^+	+ $^{6}_{3}Li$	$\rightarrow$	$^{4}_{2}He$	(1.7 MeV)	+ $^{3}_{2}He$	(2.3 MeV)			
(9)	$^{3}_{2}He$	+ $^{6}_{3}Li$	$\rightarrow$	2 $^{4}_{2}He$	+ p^+				+ 16.9 MeV	
(10)	p^+	+ $^{11}_{5}B$	$\rightarrow$	3 $^{4}_{2}He$					+ 8.7 MeV	

Notable signal/detector reactions

$^{14}N(n,p)^{14}C$	$Q = 0.626$ MeV	$E_p = 0.58$ MeV
$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{4}_{2}He + ^{7}_{3}Li + 0.48\,MeV\,\gamma$ $Q = 2.31$ MeV		$E_\alpha = 1.47$ MeV $E_{Li} = 0.84$ MeV
$^{1}H(n,\gamma)^{2}H$	$Q = 2.2$ MeV	$E_\gamma = 2.2$ MeV

https://www.nndc.bnl.gov/qcalc/

arpa·e CHANGING WHAT'S POSSIBLE

Fusion Reaction Products and Properties

H, He, etc.

Neutrons

Photons

Beta (e^{-+})

Energy(E)

Mono-energetic, Continuous

Time correlation

Charge (Z)

Rest mass (M)

Direction

Multiplicity

DOE Flickr

Non-relativistic Charge Particle Energy Loss

Alpha particles have very short ranges in solids - 10µm

Energy loss can be used to distinguish p, alphas and betas

Programs exist for accurate charged particle energy loss

$$-dE/dx \sim mz^2/E * (Z/A) * \rho$$

NIST
National Institute of Standards and Technology
Physical Meas. Laboratory

pstar — stopping-power and range tables for protons

The PSTAR program calculates stopping power and range tables for protons in various materials. Select a material and enter the desired energies or use the default energies. Energies are specified in MeV, and must be in the range from 0.001 MeV to 10000 MeV.

Help   Text version   Material composition data

Material: Water, Liquid

- **Graph stopping power:**
  - [x] Total Stopping Power
  - [ ] Electronic Stopping Power
  - [ ] Nuclear Stopping Power
- **Graph range:**
  - [ ] CSDA Range
  - [ ] Projected Range
- **Graph detour factor**
- **No graph**

Additional Energies (optional):

Use energies from a file*

Choose File No file chosen

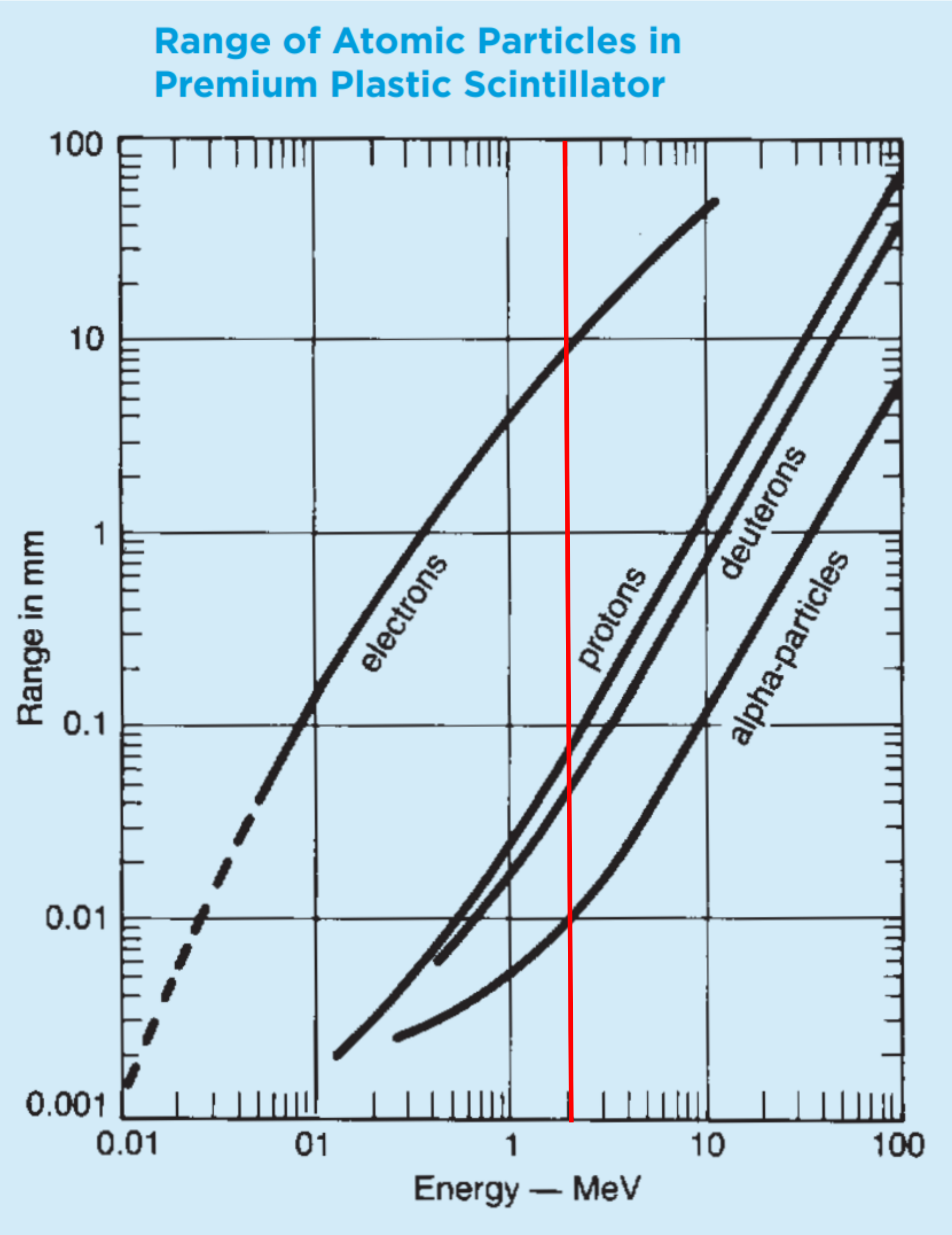
or

Use energies entered below (one per line)

[ ] Include default energies

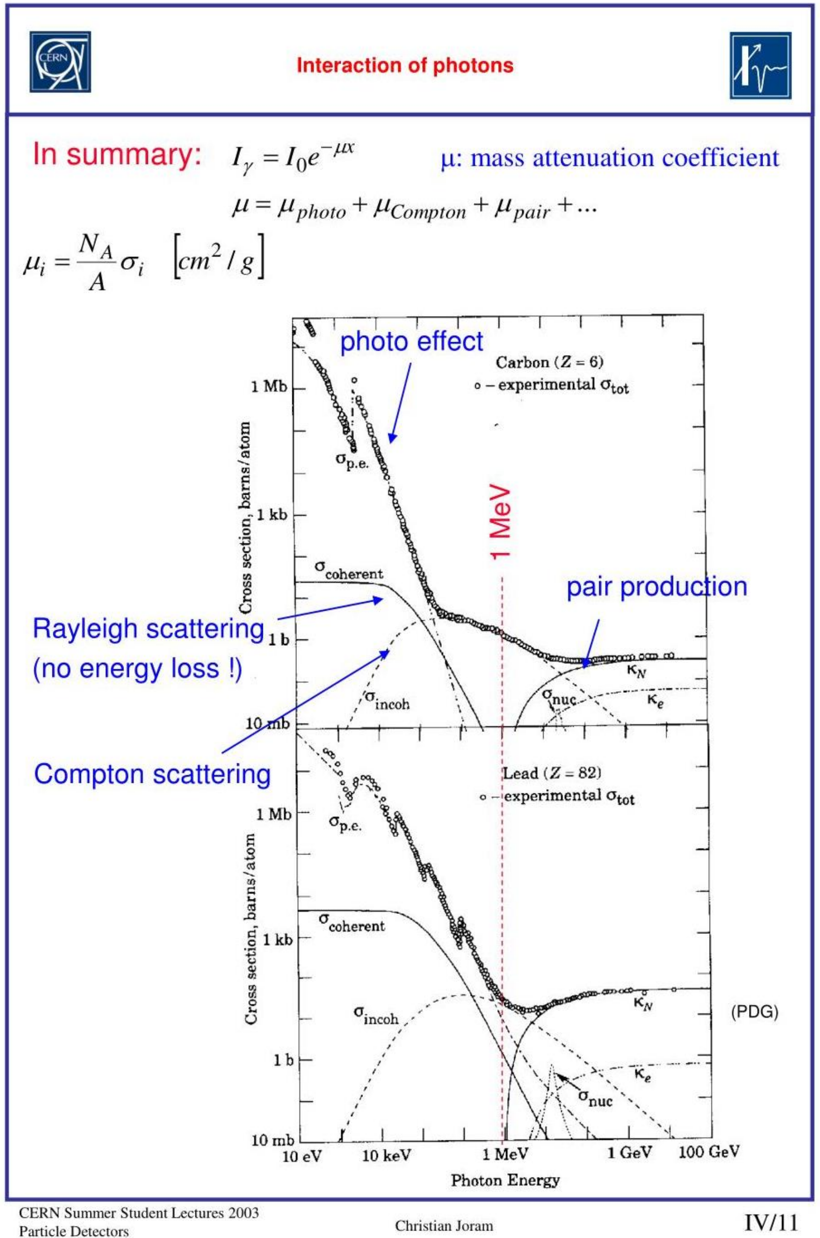
Submit Reset

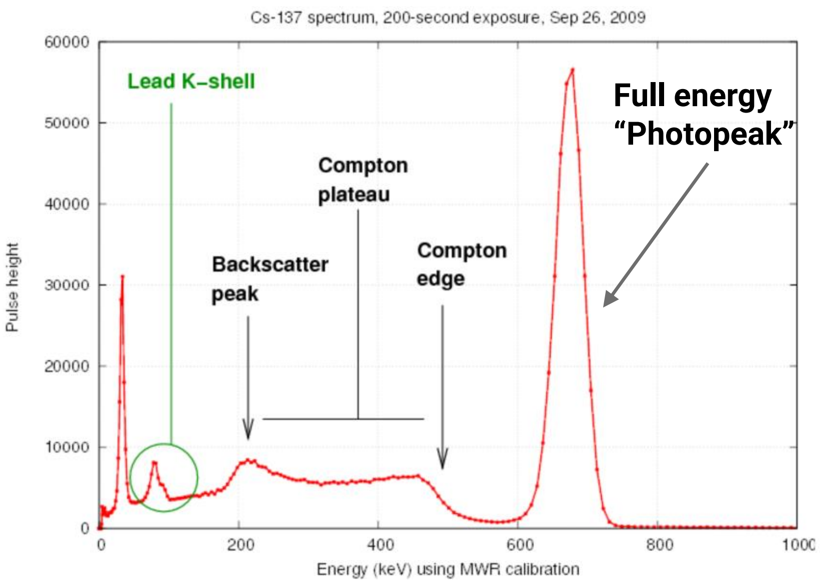
https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

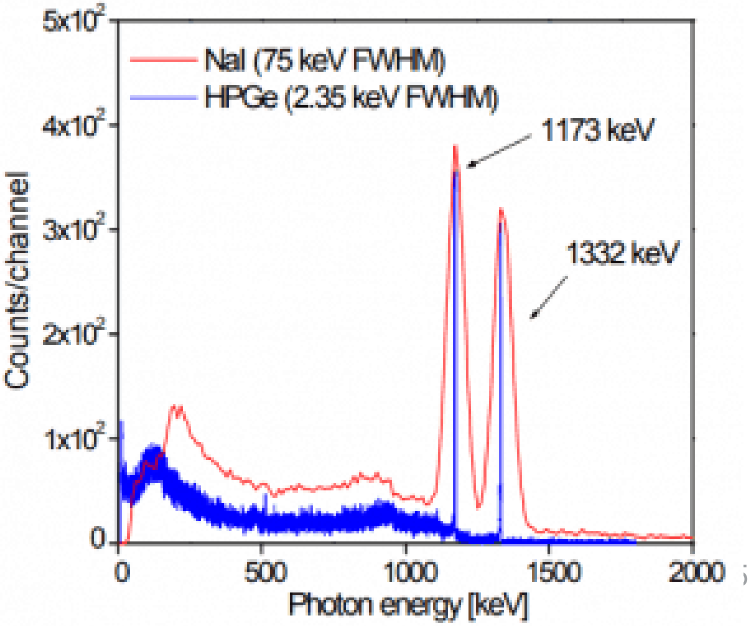


Photon Interactions

- ***MeV photons very penetrating in low-Z materials***
- ***High-Z material best for shielding***
- ***Required detector volume scales with interaction length***
- ***Materials are very important for photopeak resolution***
  - ***Photopeak not present in organic scintillators***
  - ***Photopeak requires full energy deposition***







Neutron Interactions

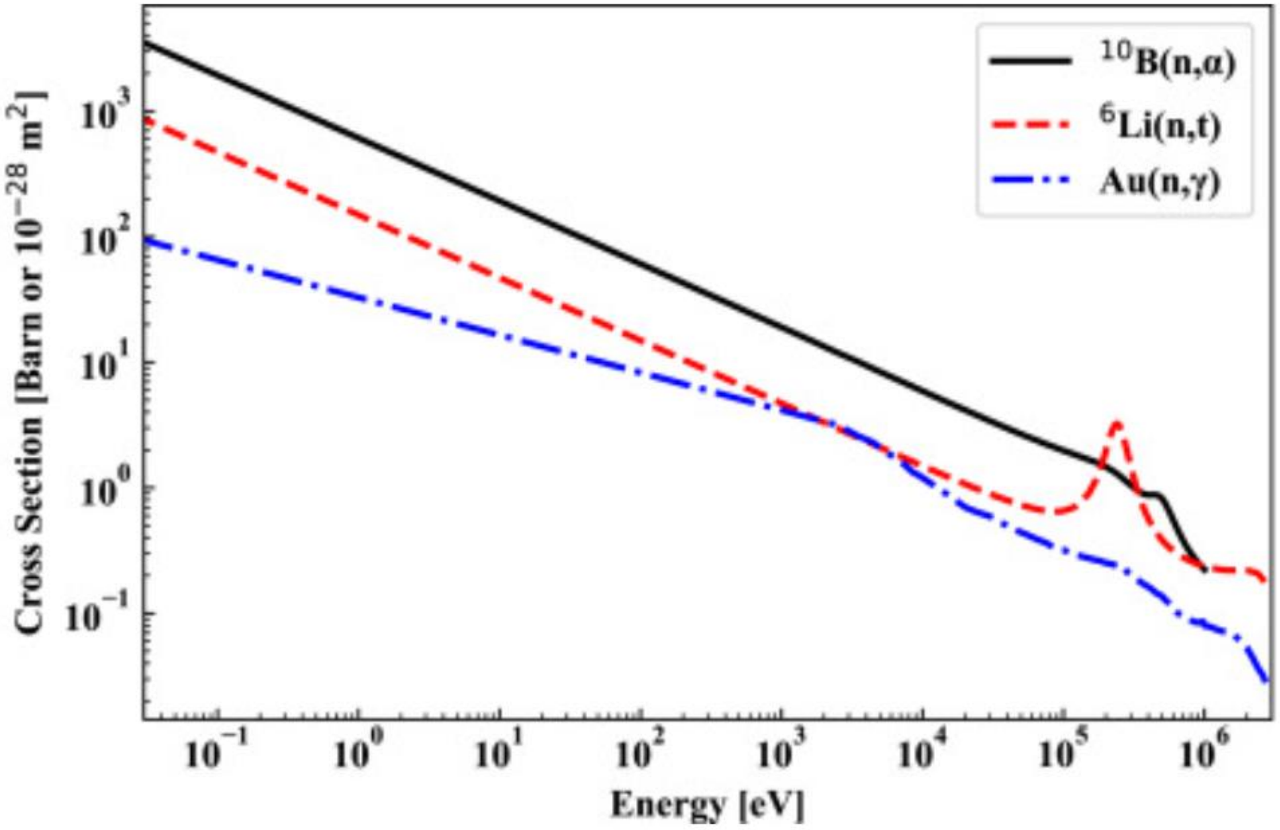
Classification of neutrons by energy

Thermal:	E < 1 eV (0.025 eV)
Epithermal:	1 eV < E < 10 keV
Fast:	> 10 keV

- *Thermal neutrons 1000x cross section of MeV neutrons*
- *High-energy n are very penetrating and provide unique signature with detection via recoil of charged particle*
- *High-energy n can be thermalized in hydrogenous materials*
- *Free neutrons have 10-minute half-life*

Thermal Neutron Cross Sections

Nuclide	*Cross section (barns)*
^{10}B	3837
^{11}B	0.005
^{12}C	0.0035
^{1}H	0.33
^{14}N	1.70
^{35}Cl	43.6
^{23}Na	0.534
^{157}Gd	254,000
^{153}Gd	0.02



Types of Particle Detectors

- CR-39
- Proportional Counters
- Semiconductor
- Scintillators

Like cars, many varieties of particle detectors exist, but they are not the same

- Strong correlation of interaction length and volume of detector
- Electronic noise and detector signal analysis are currently seldom the limiting factors in detector energy resolution
- Background is the detection of a “real” event that is not associated with the “signal”

Radiation Detection and Measurement, Glenn F. Knoll, John Wiley &Sons, Inc.

CR-39 for Neutron Detection :
Requires well-established operating procedures; minimization of background

Many variables contribute to successful use for neutron and charge particle detection

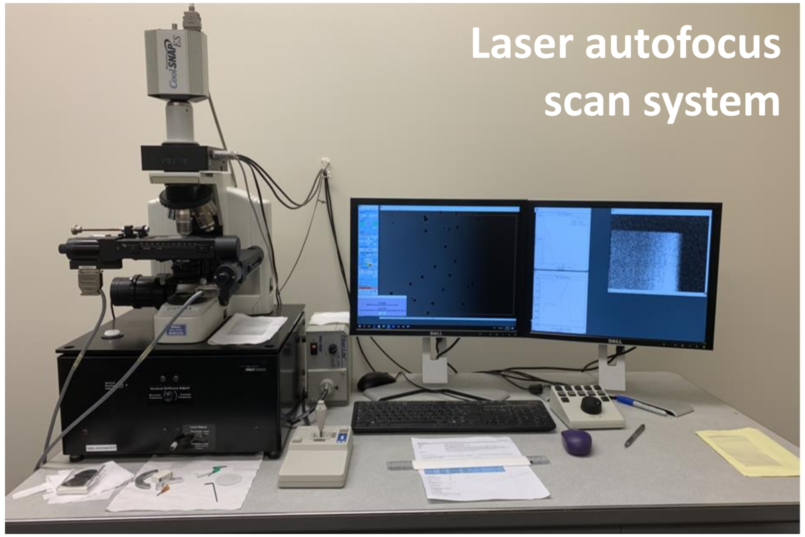
Detection 100% for charged particles, 10^{-4} n

Energy range for protons approximately 100 keV to 10 MeV

Operating procedure:

- Purchase CR-39 with moderate efficiency of detecting charged particles [high-efficiency CR-39 has high levels of intrinsic background (defects)].
- Ship CR-39 under controlled environmental conditions.
- Store CR-39 in a freezer to mitigate ageing (changes in the CR-39 detection properties).
- Develop rigorous CR-39 etch and scan procedures to understand the characteristics of neutron-induced signal tracks (size, contrast, and average eccentricity).
- Minimize handling. Minimize cleaning as it may scratch the CR-39 and generate defects that look like tracks.

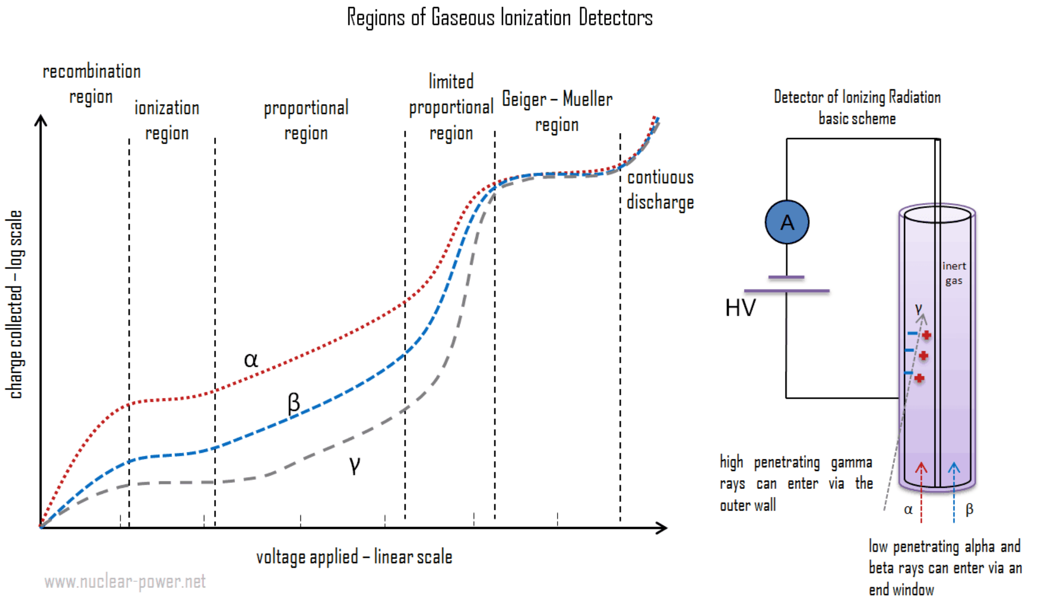
Etch for 1-6 hrs in NaOH solution for 1-6 hrs in 80°C (higher-temperature solutions will generate more defects in the CR-39)

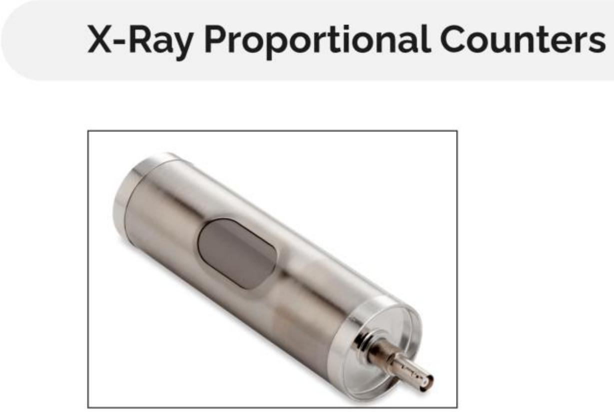


Private communication Johan Frenje, MIT

Proportional Counters for Charged Particles, n and Photons

- *Inexpensive*
- *Variety of Geometries*
- *Medium energy resolution – no direct PID*
- *High efficiency for p, α and β but <u>requires very thin window</u>*
- *OK for X-ray , low efficiency for gamma*
- *3He, Li and Boron added for thermal neutron detection via capture and charged particle decay*
- *Can be made into multi-wire configuration for large coverage – window an issue*
- *High signal gain - Simple readout electronics*



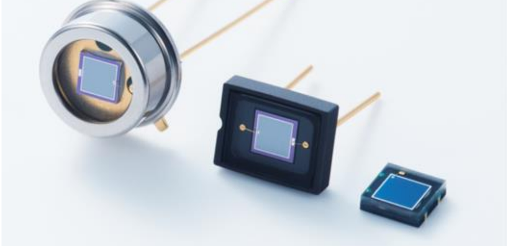


https://www.photonis.com/products/nuclear-detectors/neutron-detectors

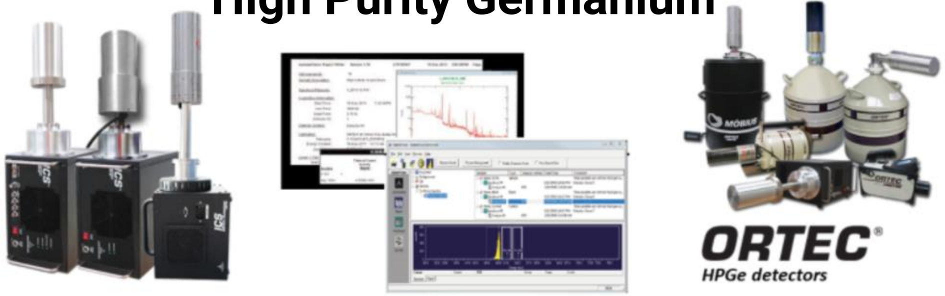
Semiconductor Detectors

- *Resolution approaches theoretical limit of e-ion pair energy of few eV with low-noise active filter electronics in direct conversion – limit .1%*
- *Many geometries possible*
- *$$$ high per volume of detector*
- *Complete commercial systems available*

PIN diodes

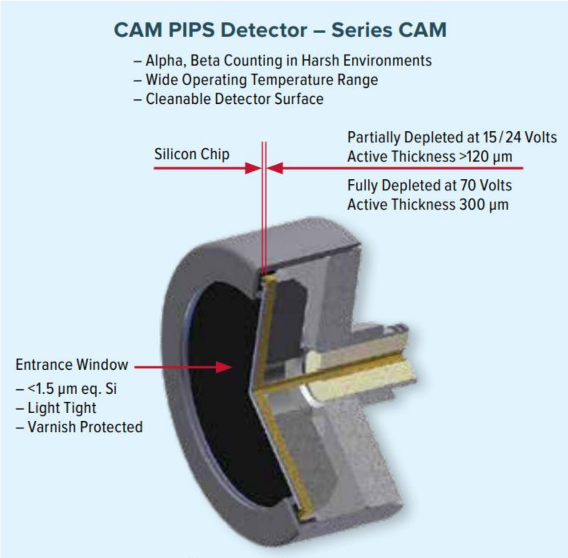


High Purity Germanium

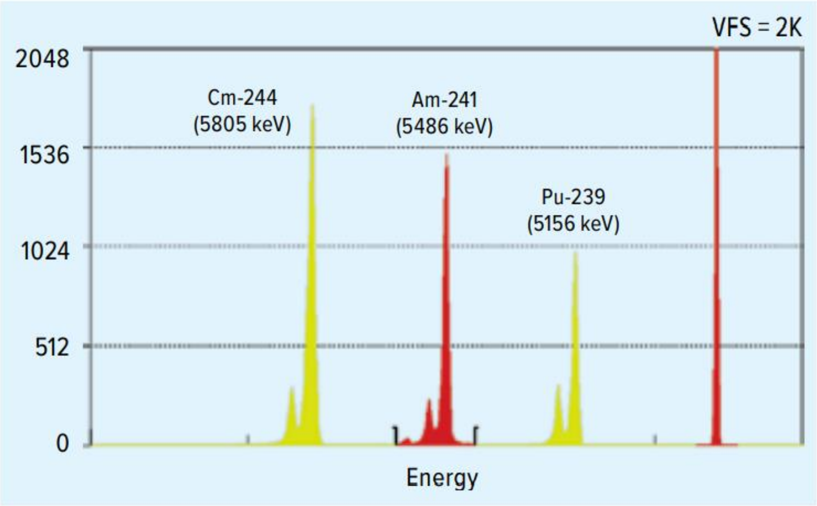


RDT Domino® Solid-State Tile Detectors
https://radectech.com/msnd_technology

Silicon planar/surface barrier
Alpha and X-ray detection



Alpha and Beta Counting

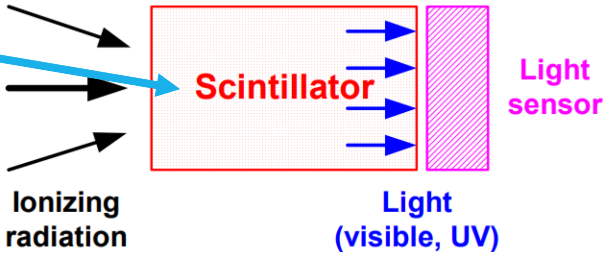


https://www.ortec-online.com/-/media/ametekortec/other/introduction-charged-particle-detectors.pdf?la=en&revision=c4921a92-598f-4e35-8672 9178f99d9449&hash=028F7B7F82E436A7BC046AF85E4ED1CD
https://www.mirion.com/products/passivated-implanted-planar-silicon-detectors

Scintillators – Swiss Army Knife of Detectors

G.F. Knoll, Radiation Detection and Measurement - 3rd edition (Chapters 16 to 18), John Wiley & Sons, 1999

Properties
- Density and Z
- Light output
- Wavelength quantum efficiency
- Mechanical/chemical stability/Temp
- Can be doped for neutron detection
- Decay Time: pile-up, integration filter



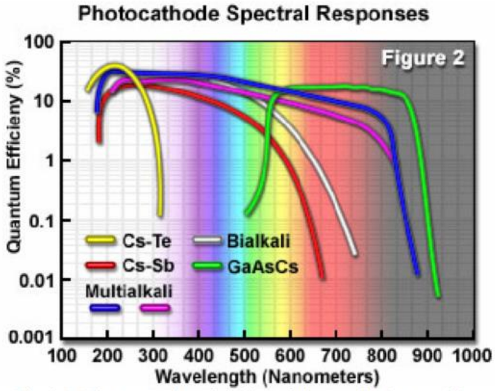
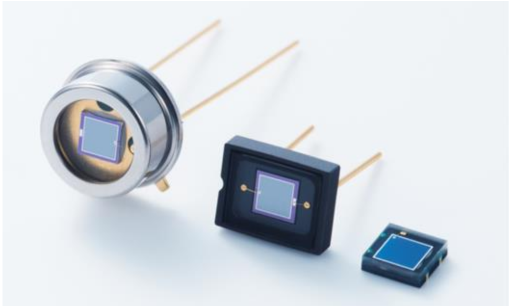


Fig. 4.7. The spectral sensitivities of photocathode materials.

- Tremendous variety of scintillators
  - Inorganic high-Z spectroscopy
  - Organic – large volume gamma and neutron counters
- Wide variety of light sensors
- Energy Resolution
  - Scintillator light output
  - Light collection geometry and coatings
  - Wavelength of scintillator and QE of sensor
- Time resolution for coincidence measurements

	NaI(Tl)	CsI(Tl)	BaF_2	BGO
Emission peak (nm)	410	565/420	310/220	480
Light yield (ph/keV)	38	65	11/1.5	8.2
Decay time				
Slow (ns)	230	680/3000	600	300
Fast (ns)			0.8	
Density (g/cm^3)	3.7	4.5	4.9	7.1
Chemical composition				Bi_4Ge_3(
$1/\mu$ (cm) at 140 keV	0.41	0.28	0.29	0.086
$1/\mu$ (cm) at 511 keV	3.1	2.4	2.3	1.1
μ_{ph}/μ (%) at 511 keV	18	22	19	44

Light Pipes



PIN diodes readout

Best energy resolution from inorganic scintillator few %, NaI, CsI closer to 7%

https://www.hamamatsu.com/jp/en/product/optical-sensors/pmt/index.html
https://www.hamamatsu.com/us/en/product/optical-sensors/photodiodes/index.html
https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/organics-plastic-scintillators.pdf

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Detector Summary

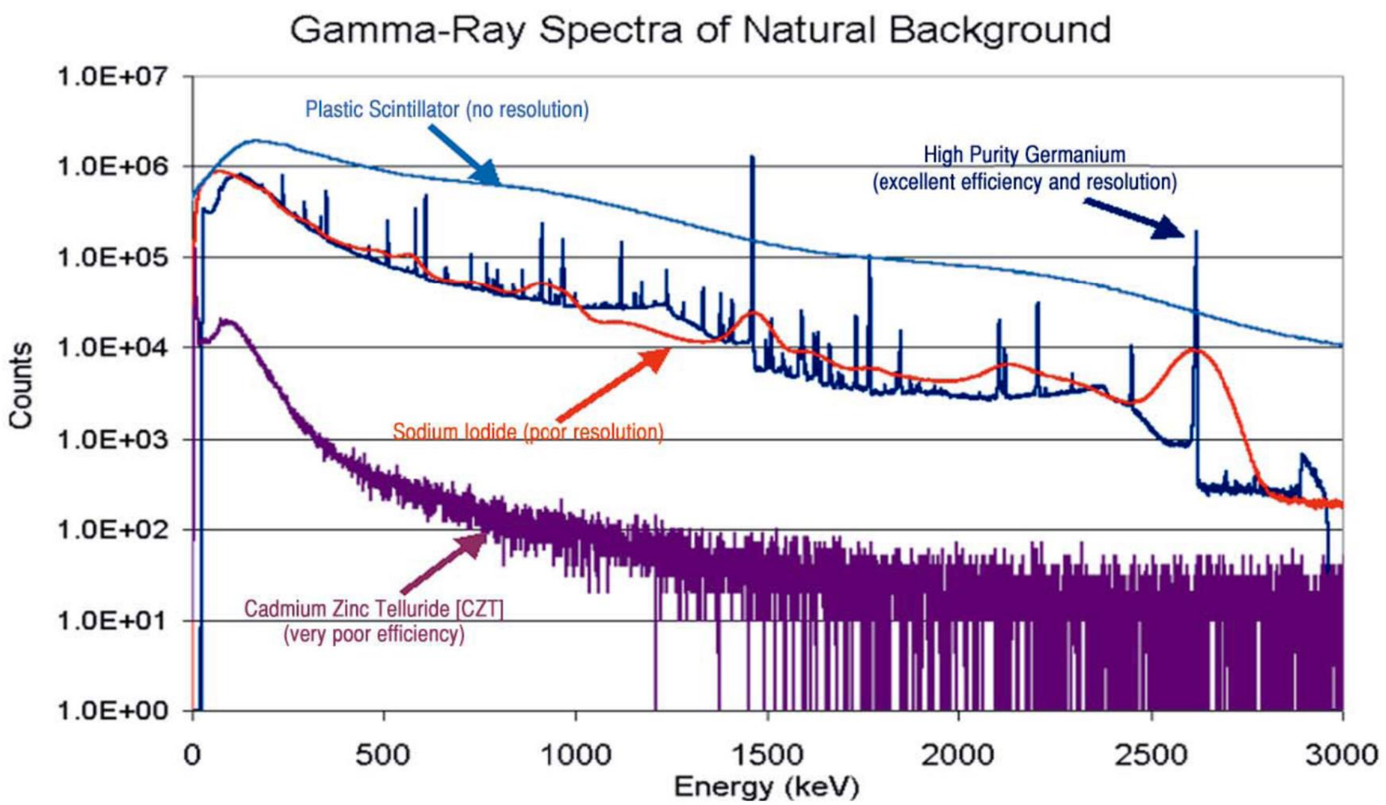
- All detectors have capabilities in the energy range .1 to few MeV
- Need to get close for charged particle measurements: use of thin windows, re-entrant ports, etc.
- Usually exists a solution that operates at elevated temp and harsh environments
- Selection often based on required detection efficiency, and energy resolution (particle dependent)
- Time correlation greatly facilitates data fusion
- Neutron detectors: thermal very efficient, fast neutrons more information

Detector Type	Pros	Cons	Sweet Spot	Cost:
CR-39	Placement options, multi-particle	Handling, processing tricky, not real time	n, Charge	$
Proportional Counters	Real time, many geometries, multi-particle	Thin windows, efficiency, low E-resolution	Charged, n, X-ray	$-$$
Semiconductor	Real time, many geometries, multi-particle, best E resolution	Cooling required for best E-resolution	All, high E-resolution	$-$$$$
Scintillators	Real time, many geometries, multi-particle	Medium E-resolution	All, medium E-resolution	$-$$

Notes on Background and Shielding

- *Very location dependent*
- *Primary radioactive decays: thorium, uranium decay chains and ^{40}K*
- *Building material background can be either a shield or source!*
- *Cosmic Rays must also be accounted for (muons and interaction products)*

Photon Natural Background

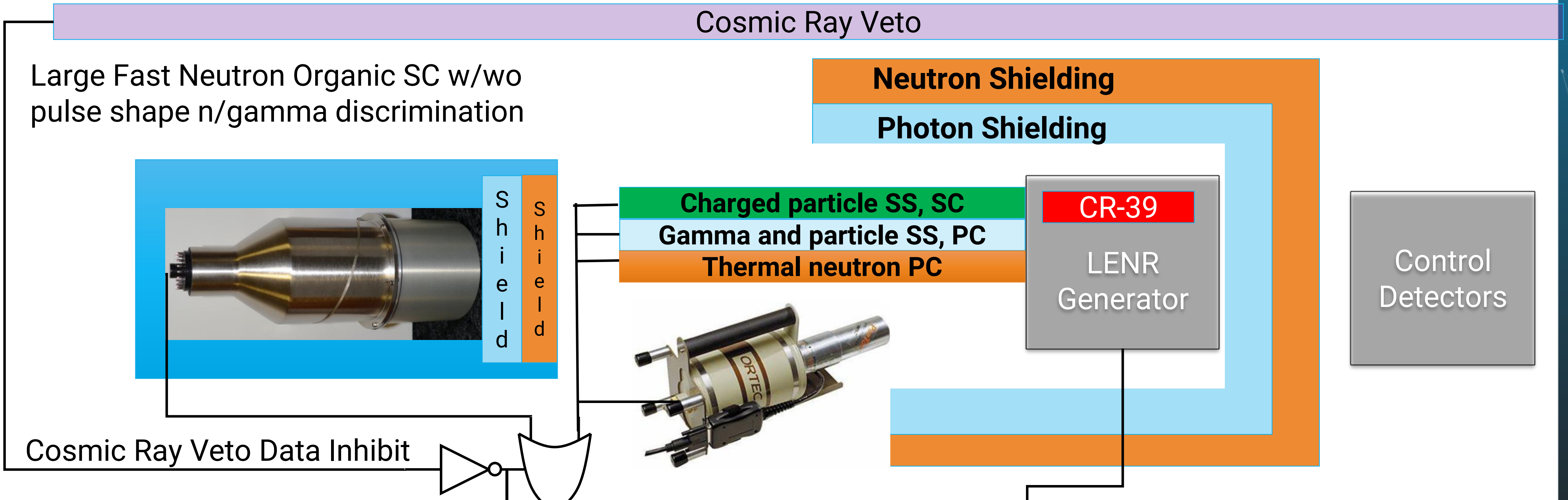


Cosmic Ray Fluxes at Sea Level

180 particles (mostly muons) /m^2/sec

Mostly muons and e^{+-}, 10 cm x 10 cm – 2 particles/sec

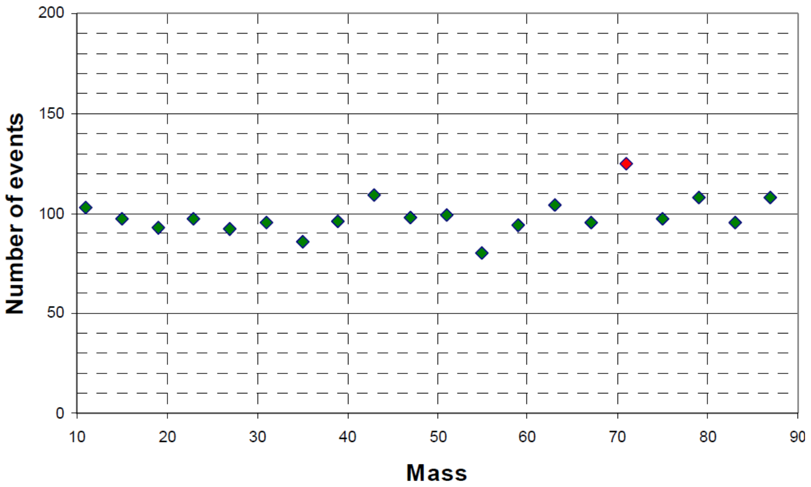
Putting it all together



Event - Time	Det. 1 n fast	Det. 2 PC	Det. 3 HPGE or SC	Det 4 n thermal	LENR Generator Data
… t_n	0	E beta	0	E thermal	Volt, temp, etc.
t_1	0	E X-ray	E gamma	0	…
t_0	E fast	0	E Gamma	0	…

SS	Solid State
SC	Scintillator
PC	Proportional Chamber
HPGE	High Purity Germanium

Determining the Confidence Level of the Signal



Significance of Measurement

"Is bin 71 consistent with a background fluctuation?"

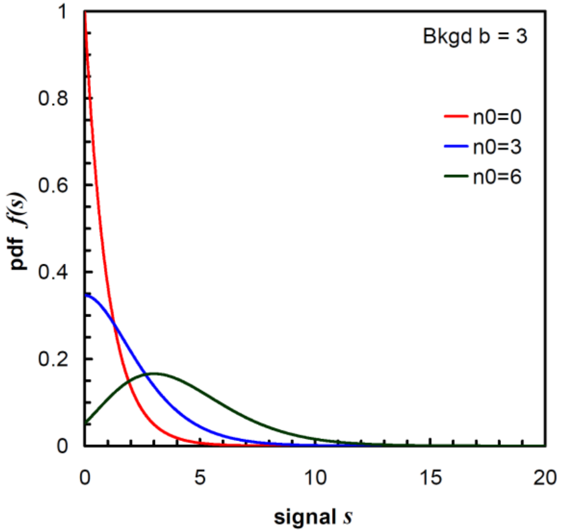
$$\text{For large } N,\ S_1 = \frac{signal}{\sqrt{bkgd}} = \frac{n_{observed} - b}{\sqrt{b}} = \frac{s}{\sqrt{b}}$$

Better approx $S_{cL} = \sqrt{2 \ln Q}$, where $Q = \dfrac{p(n_0 \mid s+b)}{p(n_0 \mid b)}$

significance	1	2	3	4	5
probability (p-value)	16%	2.3%	0.14%	3×10^{-5}	3×10^{-7}

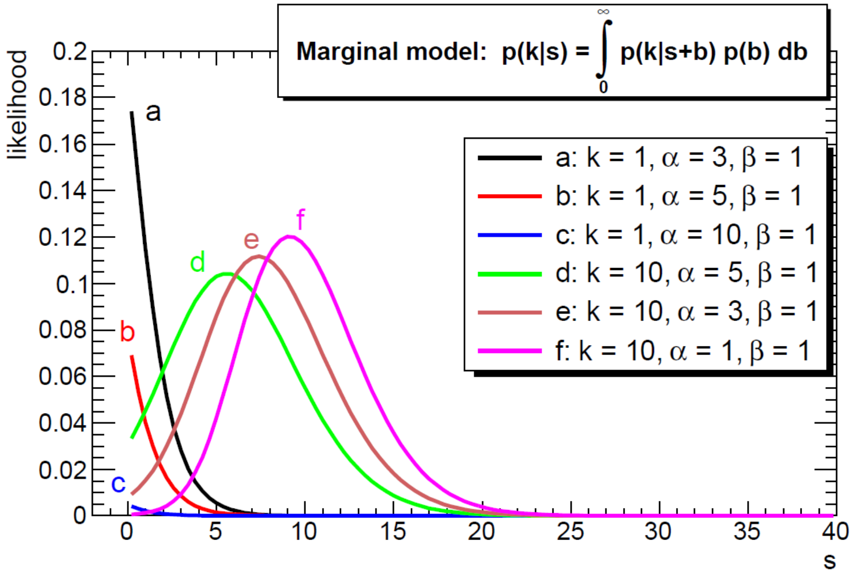
Bayesian analysis of signal likelihood in the presence of a known background

$$f(s) = p(s \mid b, n_0) = \frac{p(n_0 \mid b+s)\cdot\pi(s)}{\int_0^{+\infty} p(n_0 \mid b+s)\cdot\pi(s)\cdot ds}$$



Marginalize the background distribution

$$p(k|s) = \int_0^{\infty} \mathrm{Poi}(k|s+b)\, \mathrm{Ga}(b|\alpha,\beta)\, db$$



Bayesian analysis can be applied to multiple detector measurements and system modeling!

http://www.phys.ufl.edu/~korytov/phz6355/note_A13_statistics.pdf

arXiv:1108.4270v5 [physics.data-an] 14 Dec 2011

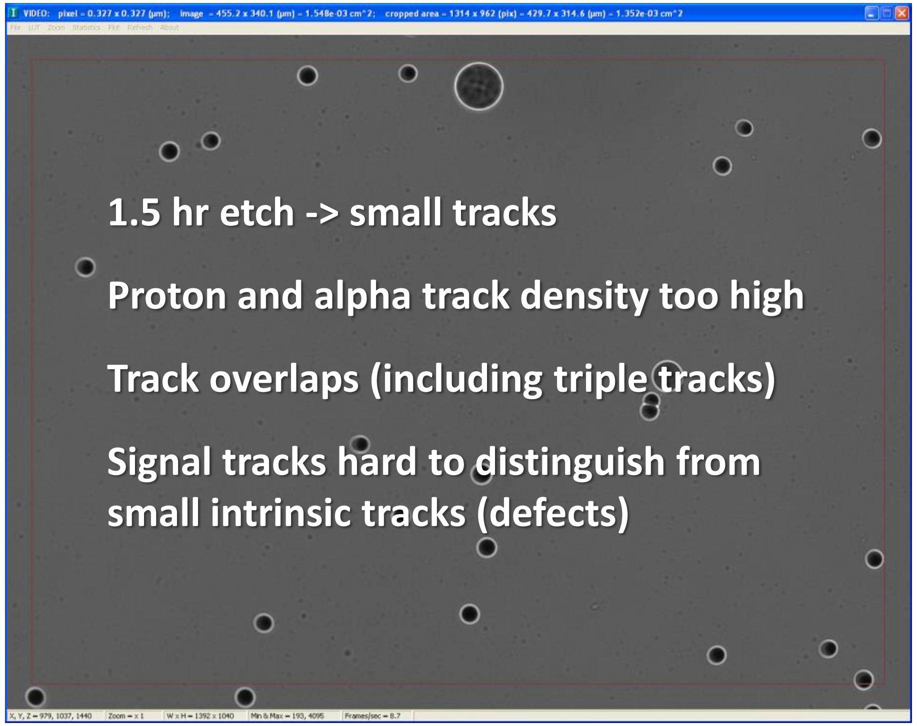
Thank You

robert.ledoux@hq.doe.gov

CR-39 for Neutron Detection:
Requires well-established operating procedures; minimization of background

Minimization of Background:

- In an experiment, minimize CR-39 exposure to heat as heat generates defects in the CR-39 that are often mistaken as signal tracks.
- Don't run an experiment for long periods of time, which could cause track overlap (either from particles or heat).
- Etch the CR-39 for long enough time to effectively separate neutron-induced tracks from intrinsic background (defects). This is done by looking at track size, darkness and ellipticity.



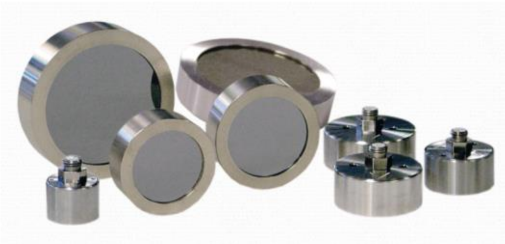
Look for typical features in the data that would indicate neutron interaction with the CR-39.

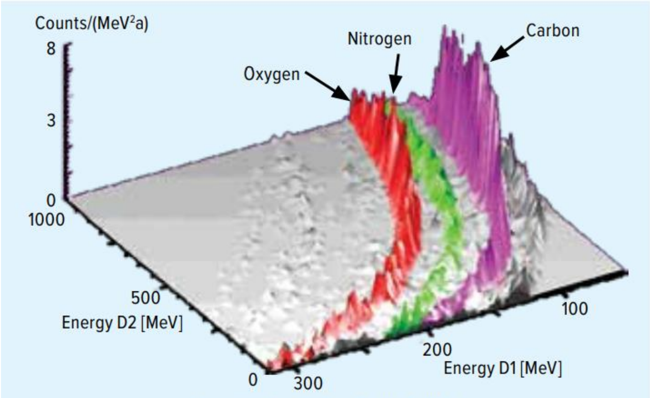
- Neutrons interact volumetrically with the CR-39 and generate a uniform distribution of tracks on the CR-39 surface.
- Neutrons generate higher levels of tracks on the backside than on the front side of the CR-39.
- In case of high-energy neutrons (> 3 MeV), tracks from several types of ions originating from elastic scattering, (n,p) and (n,α) reactions should be observed.

Private communication Johan Frenje, MIT

Backup

$$-\frac{dE}{dx} \simeq \frac{4\pi z^2 e^4}{m_e v^2}\rho\frac{Z}{A}N_0 \ln\left[\frac{m_e v^2}{\bar{I}}\right]$$





Galactic Cosmic Rays In ERNE/HED

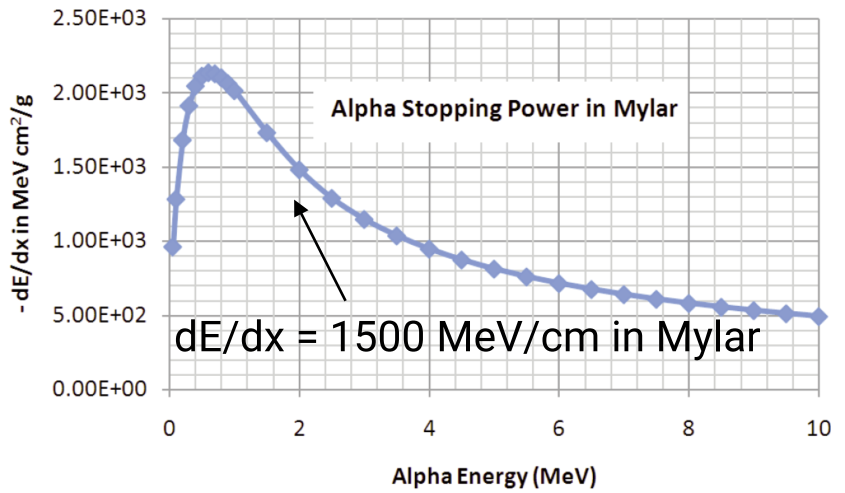


Fig. 5.2. Stopping Power for Alpha Particles in Mylar Film.

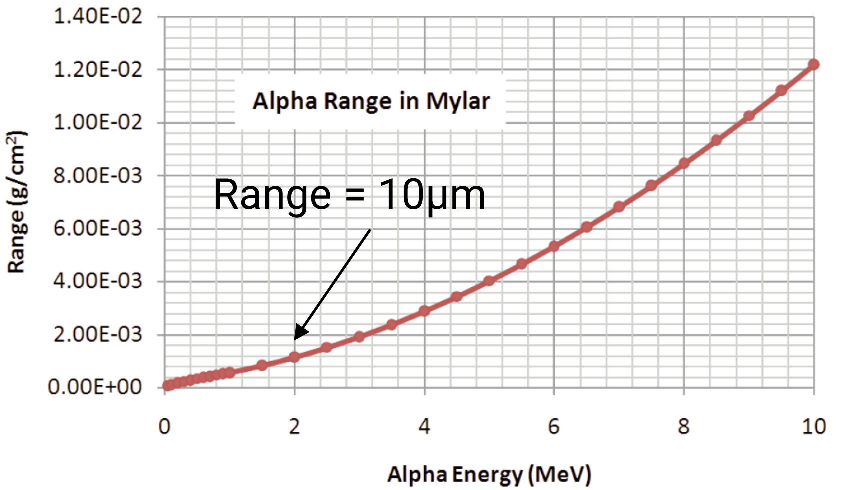


Fig. 5.3. The Range Versus Energy Curve for Alpha Particles in Mylar Film.

Other Neutron Facts

TABLE 9.4. Maximum Fraction of Energy Lost, Q_{max}/E_n from Eq. (9.3), by Neutron in Single Elastic Collision with Various Nuclei

Nucleus	Q_{max}/E_n
$^{1}_{1}H$	1.000
$^{2}_{1}H$	0.889
$^{4}_{2}He$	0.640
$^{9}_{4}Be$	0.360
$^{12}_{6}C$	0.284
$^{16}_{8}O$	0.221
$^{56}_{26}Fe$	0.069
$^{118}_{50}Sn$	0.033
$^{238}_{92}U$	0.017

Table 5.15. Averaged Number of Collisions n_{co} Required to Thermalize a 14 MeV Neutron

Element	n_{co} (from 14 MeV)	Element	n_{co} (from 14 MeV)
H	19	Al	290
C	112	Si	297
O	154	Cl	343
Mg	235	Ca	380

Hearst and Nelson (1985).

Fast Neutron Detectors

BC-523A* 10B loaded; pulse shape discrimination properties total absorption neutron spectrometry

Fusion Reaction Products and Properties

Charged Particles:

H, He, etc.

Neutrons

Photons

Beta (e^{-+})

Energy(E)

Mono-energetic, Continuous

Time correlation

Rest mass (M)

Charge (Z)

Direction

Multiplicity

https://phys.org/news/2021-03-nuclear-fusion-star-earth-hard.html